DWARF
G-APDs as photodetectors in Cherenkov Telescopes

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Outline

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Basic working principle

- An incoming photon may create an electron-hole pair.
- Due to the applied voltage V_{bias}, avalanche amplification occurs.
- For voltages above a threshold (breakdown voltage), the avalanche process is self-perpetuating (Geiger-mode).
- The resulting current induces a voltage in a serial quenching resistor, which stops the avalanche.
- Since the avalanche process is the same independently of the number of photons creating an electron-hole pair, the sensitive area is divided into cells connected in parallel.

Photon detection efficiency (PDE)

The probability, that a single photon arriving at the diode surface initiates a breakdown is called photon detection efficiency (PDE). The PDE consists of three factors:

- Part of the diode surface is not photosensitive (conductor paths) inducing a geometrical factor: ϵ_{geo}
- The probability of an incoming photon to create an electron-hole pair (quantum efficiency, QE)
- The probability that such a pair creates an avalanche (breakdown probability): ϵ_{bd}

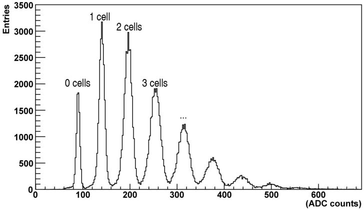
The number of photons which initiate an avalanche (N_{pe}) when N_{inc} photons arrive at the diode surface is thus

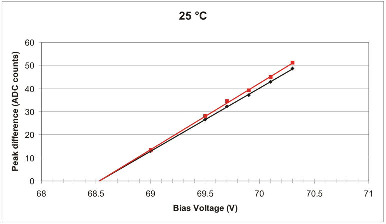
$$N_{\text{pe}} = \epsilon_{\text{geo}} \cdot QE \cdot \epsilon_{bd} \cdot N_{\text{inc}} = PDE \cdot N_{\text{inc}} \qquad (1)$$

Gain (M)

The gain is the number of electrons per breakdown. It is linear to the over-voltage, the linear coefficient is the capacitance of a single cell divided by the elementary charge:

$$M = \frac{C_c}{e}(V_\mathrm{b} - V_\mathrm{br})$$





The total signal of a light flash is the summed signal of the signals of all cells with a breakdown.

Saturation

Two incoming photons hitting the same cell contribute the same charge to the total signal as a single photon. The incoming photons are statistically distributed on the cells of the diode. If every photon hit a different cell, the number of initially triggered cells N_0 would be given by $N_0 = N_{\text{pe}} = PDE \cdot N_{\text{inc}}$. Since this is not the case, the number of initially triggered cells reduces to

$$N_0 = N_c(1 - e^{-\frac{N_{\text{pe}}}{N_c}}) \equiv S(N_{\text{pe}}, N_c)$$

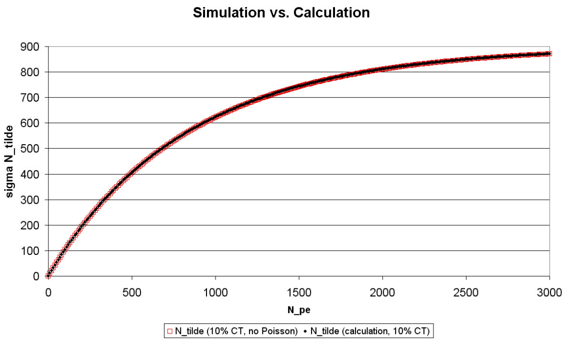
Optical Crosstalk

During the breakdown, a plasma forms in the respecting cell which emits optical photons. These may travel to neighbouring cells and initiate a breakdown in those cells. The probability that a cell with a breakdown triggers *one or more* other cells through optical crosstalk is denoted by p_{ct}. The mean number of cells triggered by crosstalk per initially triggered cell is denoted by μ_{ct}. The number of cells triggered by crosstalk is given by (including saturation effects)

$$N_{\mathrm{ct}} = S(\frac{N_c - N_0}{N_c} \cdot \mu_{ct} \cdot N_0, N_c - N_0)$$

Calculation cross-check using a simple MC simulation

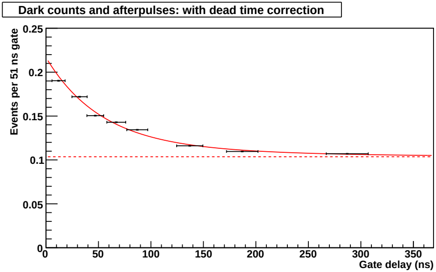
The calculation was cross-checked using a simple simulation:



The deviation is less than 0.3 percent but is not yet understood.

Afterpulses

During the breakdown, electrons may be trapped e.g. in crystal defects. The delayed release of trapped electrons occurs with exponentially decreasing probability. The first of these pulses are reduced in height due to the recovery process of the cell. They do not contribute to the pulse height, but enlarge the number of occupied cells when a light flash occurs.

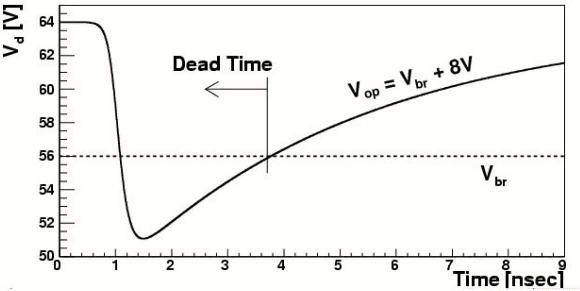


Dark count and night sky background (NSB)

- The previous slides describe the processes occurring when a light flash reaches the diode surface. Two processes create a diffuse underground which reduce the number of "free" cells for the photons of a light flash:
- Electron-hole pairs can be generated through thermal effects and tunneling. Such events are denoted as "dark counts". Hamamatsu G-APDs (called Multi-Pixel Photon Counter, MPPC) typically have a dark count rate of 2-3 MHz.
- The second process is the diffuse night sky background (NSB), which has a rate up to GHz.

Dead-time / recovery time

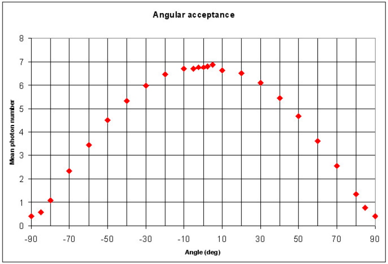
During a breakdown, the voltage over a diode cell drops *below* the breakdown voltage. The voltage recovers exponentially with a time constant of 9 ns ($50 \times 50 \mu m^2$) and 33 ns ($100 \times 100 \mu m^2$) [H. Oide, Study of afterpulsing of MPPC with waveform analysis, PoS (PD07) 008].

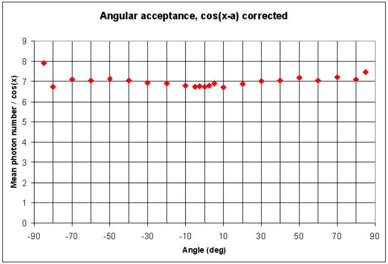


H. Oide et al. NDIP08

Angular acceptance

It was measured how the angle between the light direction and the diode surface influences the PDE. Within the measurement precision, no effect was found (except of course the reduced area...):





Further information I

- D. Renker, Characterisation of Geiger-mode avalanche photodiodes for medical imaging applications, NIM A 571, 1 (2007). [Overview]
- H. Oide et al., On the basic mechanism of Pixelized Photon Detectors, NDIP08 [Theory, simulation of the avalanche process]
- Y. Du, F. Retière, After-pulsing and cross-talk in multi-pixel photon counters, NIM A 596 (2008) 396 [Measurements, Afterpulses/crosstalk/dead time/recovery time]

Further information II

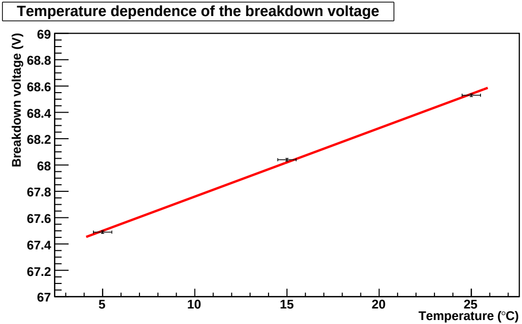
- Hamamatsu Photonics K.K., Japan, MPPC - Multi-Pixel Photon Counter (Product Specifications), 2008.
- W. J. Kindt, N. H. Shahrjerdy and H. W. van Zeijl, A silicon avalanche photodiode for single optical photon counting in the Geiger mode, Sensors and Actuators A: Physical 60, 98 (1997).
- T. Krähenbühl, G-APD and their use in axial PET modules, diploma thesis, ETH Zurich, 2008. [Overview, calculation, plots]

Calibration

The camera response is strongly dependent on the temperature and the night sky background. There are two possible calibration methods: either the gain is kept constant or a known signal (e.g. from a pulsed LED or a radioactive source). The first method makes it necessary to read out the single cell pulses, the second method is harder to interpret.

Breakdown voltage

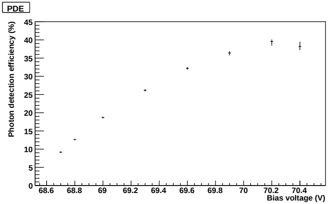
The breakdown voltage is linearly dependent on the temperature.

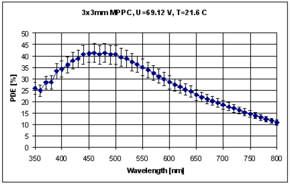


The coefficient is $52 \pm 1\,\mathrm{mV}$ per $^\circ\mathrm{C}$.

Photon detection efficiency (PDE)

The photon detection efficiency depends on the overvoltage and the wavelength of the incoming photons.





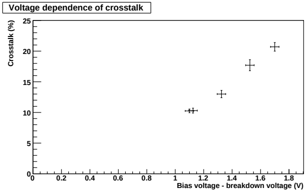
The values provided by Hamamatsu are approximately 20 percent too high (stating "PDE includes effects of crosstalk and afterpulses").

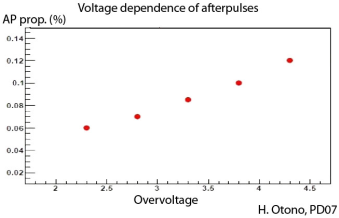
Gain / Saturation

- Gain: The gain depends on the night sky background since the increased current results in a voltage drop over the diode (serial resistor in the electronics).
- Saturation: The number of available cells is NSB dependent.

Optical Crosstalk / Afterpulses

The crosstalk depends on the extent of the avalanche and thus on the gain. The amount of afterpulses is also gain-dependent, but depends additionally on the temperature.





Calibration: Conclusion

The conclusion is that we have to keep the *gain* as constant as possible.

Hamamatsu 50C and 100C

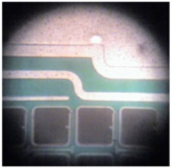
The two most-discussed G-APD types are the Hamamatsu MPPC 50C and 100C. The following table lists some of the most important characteristics:

Cell size	$50 \times 50 \mu m^2$	$100 \times 100 \mu m^2$
Package size	$6.55 \times 5.9 mm^2$	
Sensitive area	$3 \times 3 mm^2$	
Cell number	3600	900
Gain	$7.5 \cdot 10^5$	$2.4 \cdot 10^6$
(Pulse height)	only slightly smaller for the 50 μm type since the signal tail is much smaller	
Fill factor ϵ_{geo}	61.5 %	78.5 %
Recovery time constant	9 ns	33 ns

- The most important question is: if we see a certain pulse height, with which precision can we reconstruct the initial number of incoming photons?
- The reconstruction precision (neglecting gain variations, NSB and afterpulses) is dominated by the number of incoming photons times the PDE (Poisson statistics) and the statistical effect of the saturation.
- Pro 100C: The PDE is larger due to the larger fill factor, thus better Poisson statistics
- Pro 50C: larger cell number, thus better saturation properties
- When neglecting afterpulses and NSB, the reconstruction precision is comparable.
- The effect of the NSB, gain variations and afterpulses will shift the advantage to the 50C cells.

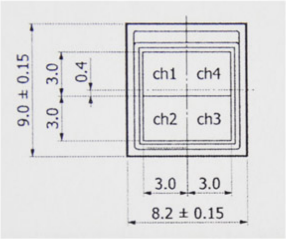
Slides by Dieter Renker:

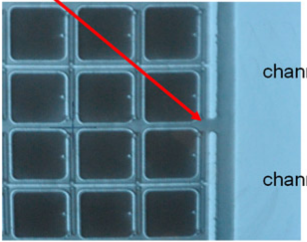
2x2 G-APD



Chip size:	6x6 mm^2
Channels:	4 ch, each 3x3 mm^2
Package:	9.0 x 8.2 mm^2

No additional dead space between the channels. Separation by gaps in the connecting Al-lines

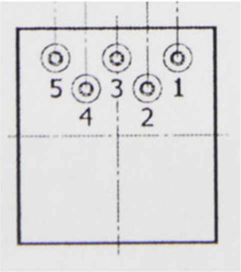




Slides by Dieter Renker:

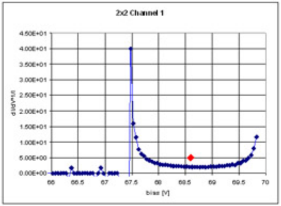
2x2 G-APD

5 pins: common cathode, separate anodes



Hamamatsu data for the 4 channels

1	68.58V	4.87 MHz
2	68.53	4.83
3	68.55	4.36
4	68.52	4.27



Slides by Dieter Renker:

2x2 G-APD

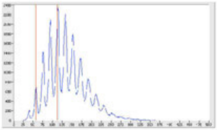
- Spectral response
- Operating Voltage
- Dark count rate
- Terminal capacitance
- Gain
- Optical crosstalk

} Identical to single channel diodes

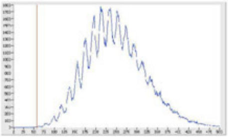
Crosstalk between the cells is very small (~2 %)

Slides by Dieter Renker:

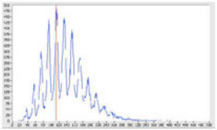
2x2 G-APD



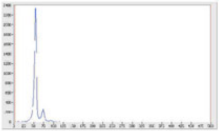
Channel 1



Sum of channel 1 and 2



Channel 2



Dark counts with optical crosstalk events

4

Slides by Dieter Renker:

Prices

MPPC 2x2 array (6x6 mm^2)

Pieces	Price in Yen	Price in CHF	Price/mm^2 in CHF
1000	55000	550	15.28
10000	18000	180	5.00
100000	7000	70	1.94

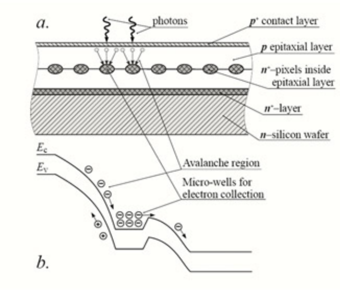
MPPC single channel 3x3 mm^2

Our price	130	14.44
EUSO (20.000 pieces)	39	4.33

Slides by Dieter Renker:

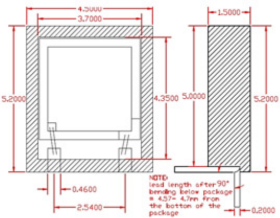
Competition

Zecotek produces 3x3 mm^2 G-APD's based on ideas of Z. Sadygov (JINR, Dubna). Quenching by space charge and not by individual resistors.



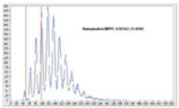
The devices have a very high density of cells: 15,000 cells/mm^2 - 135.000 cells in total.

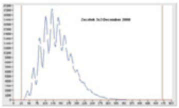
The gain of 10^5 is relative low.

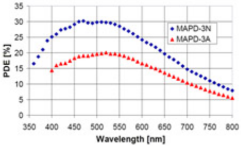


Slides by Dieter Renker:

Zecotek







PDE and spectral sensitivity similar to the Hamamatsu device S10362-33-050C

The resolution is worse compared to Hamamatsu because of the low gain and therefore higher contribution of the amplifier noise

Very small dark currents ~50 nA

Low dark count rate <1.5 MHz

Optical crosstalk <15 %

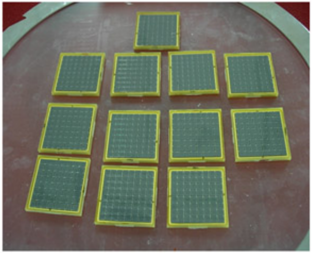
Low number of afterpulses

Slides by Dieter Renker:

Price

Unknown yet but certainly lower than Hamamatsu

8 inch wafer produced by Zecotek



The production yield cannot be too bad: monolithic arrays of 8x8 G-APDs with areas of 3x3 mm^2 each from Zecotek (> 95 % according to the producer)

Modul 0 testing procedure (outline)

Stage 0 Basic operating, line check: does every pixel give a signal on the right channel?

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Stage 1 Signal and trigger check: linearity, voltage dependence, single p.e. signals

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- Stage 2 Working under NSB conditions

Modul 0 testing procedure (outline)

Stage 0 Basic operating, line check: does every pixel give a signal on the right channel?

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Stage 2 Working under NSB conditions

Stage 3 Working under changing conditions (temperature, NSB, without cooling)

Modul 0 testing procedure (outline)

Stage 0 Basic operating, line check: does every pixel give a signal on the right channel?

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Stage 2 Working under NSB conditions

Stage 3 Working under changing conditions (temperature, NSB, without cooling)

Stage 4 First outdoor testing

Modul 0 testing procedure (outline)

- Stage 0 Basic operating, line check: does every pixel give a signal on the right channel?
- Stage 1 Signal and trigger check: linearity, voltage dependence, single p.e. signals
- Stage 2 Working under NSB conditions
- Stage 3 Working under changing conditions (temperature, NSB, without cooling)
- Stage 4 First outdoor testing
- Stage 5 Installation on La Palma (?)

Outlook

For a precise reconstruction, most of the parameters and their dependencies must be known with greater precision. Also the stability between different G-APDs has to be investigated. These parameters include

- $V_{\mathrm{Hamamatsu}} - V_{\mathrm{bd}}$
- gain vs. overvoltage
- PDE
- crosstalk
- temperature dependence of V_{bd}.

All parameters (except the breakdown voltage) are assumed to be identical between the G-APDs within the required precision.
Further questions have to be answered, e.g. the distribution of the photons on the chip surface, which influences the saturation behaviour.

Questions?